SILICON WAFER BONDING WITH AN INSULATOR INTERLAYER USING RF DIELECTRIC HEATING

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ABSTRACT

A new silicon wafer bonding process based on dielectric heating of an intermediate layer has been developed and characterized. This method uses a capacitive RF field to heat a dielectric interlayer up to its glass transition temperature and permanently join two wafers. A 500 W 14 MHz source was used to deliver RF power to the substrates. Two inches diameter silicon wafers with 2-20 μm thick polyimide intermediate layers were successfully bonded (> 95% bond area) in less than 7 minutes. The silicon substrate temperature remained below 280 °C throughout the bonding process. The results of the pull tests indicate a bond strength of > 1.5 MPa for fully cured substrates, which is greater than the strength of other low-temperature adhesive bonds.

INTRODUCTION

Wafer bonding is among the most important fabrication techniques in microsystem technology [1]. It is frequently used to fabricate complex 3-D structures both as a functional unit and as a part of the final microsystem package and encapsulation. Recently, there has been a surge of interest in alternative bonding techniques to the common silicon-silicon fusion and silicon-glass electrostatic methods. These include low-temperature adhesive bonding [2], microwave bonding of silicon wafers with a metal interlayer [3], and silicon-silicon fusion bonding using inductive heating [4]. These techniques mostly try to augment the fusion and electrostatic methods by reducing the bond temperature and/or time. However, these methods suffer from several shortcomings. They are either, low-strength and non-hermetic (e.g., adhesive bonds), or require elaborate systems such as microwave source and cavity resonators. Inductive heating requires a complex magnetic field configuration to uniformly heat the silicon wafer to 800-1000 °C.

In this paper, we present a new wafer bonding technique using RF dielectric heating. This method has several important advantages compared to other techniques. It is fast (<7 minutes bonding time), has a simple RF field configuration, is void free, and the bond is stronger than reported adhesive bonds. RF dielectric heating uses a high frequency electric field to impart energy to an insulator placed between two metallic electrodes in a parallel plate capacitive configuration. Considerable energy can be imparted to dielectric molecules by agitating them as the field alternates each cycle. This energy appears as heat and since it is developed directly in the material, excellent uniformity and remarkable speed of heating are possible. In the following sections, we will describe the theory of dielectric heating followed by the bonding setup, test results, and discussion.

THEORY OF DIELECTRIC HEATING

Dielectric heating is normally used to moderately heat materials that have a low thermal conductivity such as rubber, wood, and glue [5]. This technique relies on the dissipative behavior of an imperfect dielectric in an electromagnetic field. If a sinusoidal electric field ($\vec{E}$) with a frequency of ω is applied to a lossy dielectric, the electric displacement vector ($\vec{D}$) can be written as

$$\vec{D} = (\varepsilon' + j\varepsilon'') \cdot \vec{E} \qquad (1)$$

where ε' and ε'' are the real and imaginary parts of the dielectric constant, respectively. The imaginary part represents the resistive dissipation in the dielectric. Assuming a parallel plate capacitive structure, the power dissipated in the dielectric can be written as:

$$P = \frac{\omega V^2 \varepsilon' A \tan\delta}{d} \qquad (2)$$

where A is the electrode area, d is the dielectric thickness, and $\tan\delta$ is the loss tangent given by:

$$\tan\delta = \frac{\varepsilon'' + \frac{\sigma}{\omega}}{\varepsilon'} \qquad (3)$$

where σ is the conductivity of the material. As can be seen from (2), the dissipated power depends on several important electrical and material factors. It is directly proportional to the frequency, the square of the applied voltage, and the loss tangent of the material. The frequency is usually chosen in the 10-30 MHz range [5]. The upper limit of the voltage is dictated by the dielectric

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breakdown and corona discharge. Several materials can be considered as possible dielectric interlayers in silicon-silicon bonding. These include glass, phospho-silicate glass (PSG), low-temperature-oxide (LTO), photoresist, and polyimide. Important considerations with regard to the material are the glass transition temperature and loss tangent. Table 1 shows these and some other properties of the possible intermediate layer candidates for silicon bonding. Polyimide was chosen as the primary material in this work for its relatively high dielectric loss and low glass transition temperature.

Table 1: Material data for several important dielectrics.

Material	Photoresist	Polyimide	PSG	Pyrex Glass
Glass Transition Temp.°C	145-180	325-400	1000-1100	550-600
Loss Tangent	0.0006-0.0010	0.013-0.015	$<1x10^{-5}$	$1.5x10^{-5}$
Specific Heat Capacity, J/kg°C	1500-2000	2000	800	750
Thermal Conductivity W/m°C	0.2	0.16	1.0-1.2	1.3-1.7

Two silicon wafers with an intermediate dielectric layer can be modeled with an equivalent RC circuit shown in Figure 1. The capacitors represent the normal dielectric response of the substrates to the electric fields, while the resistors depict the effect of dielectric loss and are given by:

$$R = \frac{d}{A \cdot (\sigma + \omega \varepsilon'')} \qquad (4)$$

This equivalent circuit model can be used to estimate the dissipated power in the silicon substrates and the dielectric interlayer.

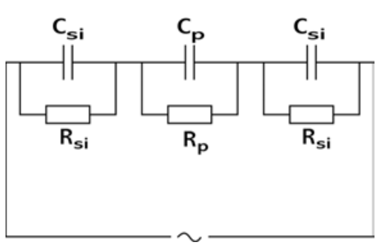

Figure1. Equivalent circuit model of two substrates with a dielectric intermediate layer.

BONDING SETUP AND PROCEDURE

Figure 2 shows the experimental setup for bonding silicon wafers using RF dielectric heating. A signal source (Kenwood TS 430, 100 W RF output power) and an amplifier (500W maximum output power) were used to deliver RF power at a frequency of 14 MHz to a sandwich of two wafers coated with a dielectric interlayer. For our bonding tests we used a clamp designed for wafers up to 3" in diameter. The clamping pressure ranged from 1 to 4 bar. The clamp includes a pair of aluminum electrodes to deliver RF power to the silicon-dielectric sandwich layer and two thick plastic sheets for thermal insulation (this shortens the time required to bring the polymer to its glass transition temperature since the power dissipated in silicon also contributes to the heating of the dielectric interlayer). With high conductivity metal electrodes most of the RF power is delivered to the dielectric layer, however, certain amount of resistive power is dissipated in the silicon substrates.

The bonding procedure consists of the following steps: 1) the wafers are thoroughly cleaned, 2) the polymer interlayer is spun and fully cured, 3) the wafers are clamped, and 4) the RF power source is turned on for a period of 3-7 minutes (depending on the material used as an intermediate layer and its thickness). The bonding procedure can be done in a standard vacuum chamber as suggested in [2]. However, in our experiments, the procedure was performed at ambient pressure. In contrast to [2], where curing of polymers was done after applying pressure, all polymer coatings in our tests were cured fully prior to joining the wafers to remove all the solvents; this prevents out-gassing and void formation, which is a common problem in low-temperature adhesive bonding techniques.

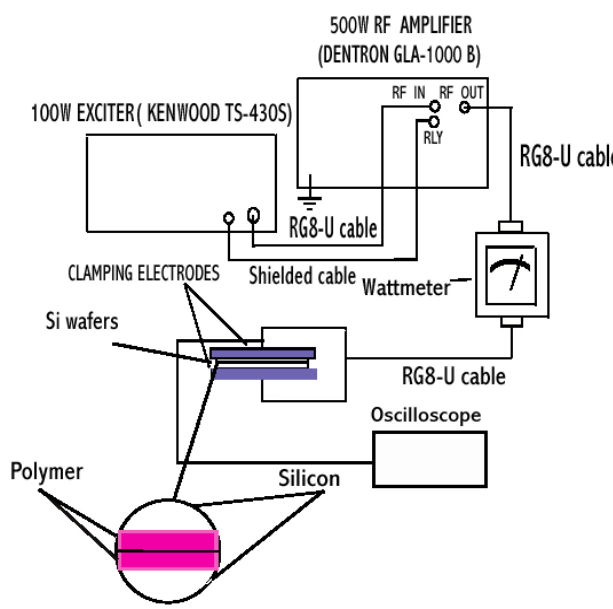

Figure 2. Experimental setup for bonding silicon wafers using RF dielectric heating

TEST RESULTS

Two inches diameter 300 µm thick silicon wafers with 1-20 µm thick polyimide and photoresist interlayers were used in our experiments. Several different photoresists (S1818, S1805) and polyimides (PI2574, PI2560, PI2610) were investigated. A total number of 20 bonds were performed using different dielectric interlayers. Bonding conditions for each dielectric interlayer are given in Table 2. We used a thermocouple to measure the temperature of the outer surface of the electrode immediately after the completion of the bonding process. The heating of the surface was almost uniform (<3% variations across the wafer) indicating a good uniformity of the internal heating.

Table 2: A summary of the material data and experimental conditions for the polymers used in the bonding tests. The RF power level is 500 W, frequency 14 MHz.

Polymer	S1818	S1805	PI 2574	PI2610	PI 2560
Glass Transition Temp.°C	145-160	145-160	325	360	400
Thickness, µm	2	0.5	12	3	3
Applied Voltage (V rms)	150	160	180	175	165
Minimum Bonding Time, min	6	4	5	3.5	4
Estimated Temp. at the Junction, °C	320-340	330-345	350-370	390-410	390-400

Several methods were used to determine the quality of the bonds. These included: 1) measurement of the tensile strength, 2) SEM inspection of the cross-section, 3) blade test (e.g. splitting two bonded wafers with a razor blade), and 4) bonding of a silicon substrate to a glass wafer allowing visual inspection over large areas. The influence of the clamping pressure and the bonding time on the bond quality was also investigated. For each dielectric material there existed a minimum time required to obtain a good bond (table 2). Clamping pressures below P_c=1.2 bar provide low quality bonds (bond strength smaller than 0.2 MPa) for polyimide intermediate coatings, whereas for photoresist, this critical pressure is P_c=1.9 bar. The bond strengths reached maximum values (Table 3) at clamping pressures 0.2-0.3 bar above P_c.

The results of the pull tests for different materials are summarized in Table 3. These indicate the bond strength of > 1.5 MPa for fully cured polyimide (PI 2574) substrates which is greater than other low-temperature adhesive bonds. The bond strength of the wafers with intermediate photoresist layers was substantially lower (table 3). The bond quality was also evaluated by splitting the wafers with a razor blade. Separation of the wafers with a polyimide intermediate layer was impossible, whereas splitting the wafers with a photoresist coating was relatively easy.

In order to evaluate the void formation at the bond interface, silicon wafers were bonded to 300 µm thick glass wafers. Polyimide yielded superior results with regard to the void formation. Figure 3 shows the photograph of a silicon substrate with a cured polyimide (PI2560, thickness 2 µm) bonded to a 300 µm thick glass wafer. As can be seen more than 95% of the area is uniformly bonded. We also performed bonding of wafers with pre-cured polymers. As can be seen from fig. 4, large voids due to out-gassing are present at the bond interface. The measured bond strength, as can be expected, is much lower for pre-cured than for fully cured polymers (table 3).

Table 3. Measurements of tensile bonding strength for different polymers.

Polymer	**S1818**	**S1805**	**PI2574**	**PI2610**	**PI2560**
Bond strength (cured polymer), MPa	0.5-0.7	0.5-0.6	1.5-1.6	1.0-1.1	0.9-1.1
Bond strength (pre-cured polymer), MPa	0.2-0.3	0.2-0.3	0.4-0.5	0.3-0.4	0.3-0.4

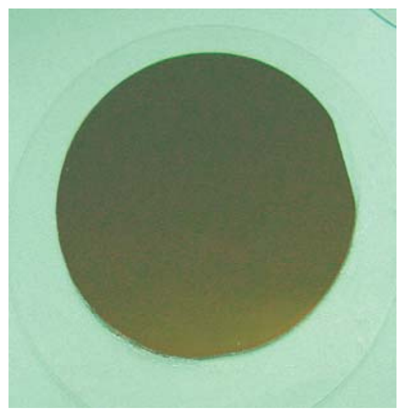

Figure 3. Photograph of a 2” diameter silicon substrate with fully cured polyimide bonded to a glass wafer.

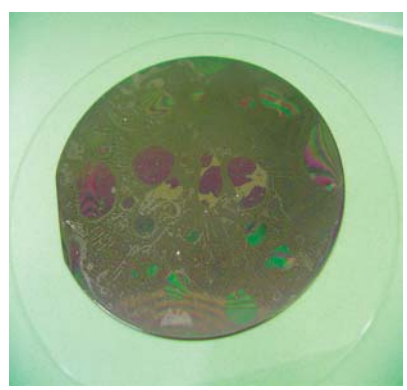

Figure 4. Photograph of a 2” silicon substrate with uncured polyimide bonded to a glass wafer.

Figure 5 is the SEM cross-section of two bonded silicon substrates showing the complete joining of the intermediate polyimide layers. This is due to the full transition of the intermediate layer to the glassy state.

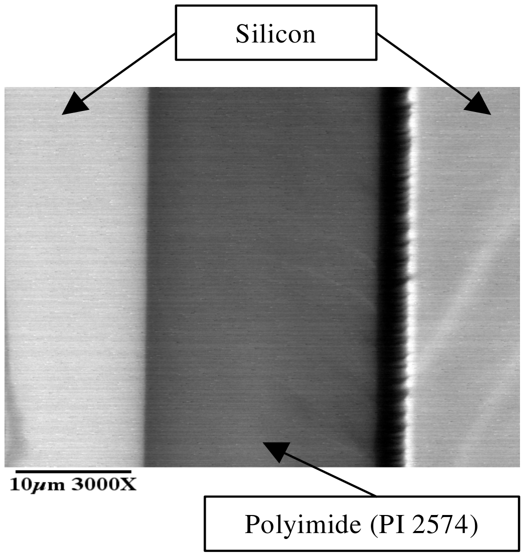

Figure 5. SEM cross-section of two bonded silicon substrates showing the complete transition to the glassy state and joining of the polyimide layers.

DISCUSSION

In contrast to other techniques, silicon-silicon bonding using RF dielectric heating does not require bringing the whole system to a high temperature since heat is generated within the interlayer. Thus, the substrates are kept at a lower temperature than the intermediate layer. Technologically, this is advantageous for bonding wafers with low melting temperature metal films on top such as Al. Steady-state differential equation of heat conduction can be used to calculate the temperatures of the interlayer and the substrates. The temperature can be assumed to be uniform in the lateral dimension, i.e., parallel to the surface of the wafer. Using this technique,. the temperature of the outer surface of silicon was calculated to be 260-280˚C, which is lower than the glass transition temperature of polyimide (325-400˚C). The dielectric loss tangent and the thermal conductivity of the substrates and the intermediate layer are functions of temperature. The values used for the calculations of the dissipative power are the averages in the 50-500°C interval.

RF amplifier (Dentron GLA-1000) delivers its maximum output power when the load is matched (50 Ohm). Analysis shows that the silicon-silicon sandwich with a dielectric interlayer represents a mostly capacitive load that varies during the bonding process. This presents an unmatched variable load to the RF source, which requires a tuning compensation network. Without the matching tuner, more heat is dissipated in the amplifier internal circuitry. This reduces the duty cycle of the amplifier and degrades its performance.

We have focused on polymers and have not explored the bonding of silicon wafers with PSG, LTO, or glass as intermediate layers. A very low loss tangent ($1.5x10^{-5}$) in the 10-30 MHz range and a high glass transition temperature (T_g-600˚C) make Pyrex glass unsuitable as an intermediate layer. PSG has even a higher glass transition temperature (1000-1100˚C) and lower loss tangent. However, the use of these materials as intermediate layers for dielectric bonding is possible with a more powerful RF exciter. Several other candidates for dielectric interlayer include polyamide (loss tangent 0.16), phenol-formaldehyde resin (0.2) and polyvinyl chloride (0.4); however, these materials are not common in the MEMS technology.

CONCLUSION

In this paper, silicon-silicon and silicon-glass wafer bonding using RF dielectric heating of intermediate polymer coatings were demonstrated and characterized. Several polyimides and photoresists were tested as intermediate layers. Void formation at the bond interface and the bond strength for fully cured and pre-cured polymers were evaluated. The influence of the clamping pressure and bonding time on the bond quality was also characterized. Polyimide gives superior results with regard to bond strength and void formation. The results of the pull tests indicate the bond strength > 1.5 MPa for fully cured PI 2574 polyimide intermediate layers, which is higher than the strength of other low-temperature adhesive bonds.

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